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WEATHERING STAGE OF TILL AND GLACIAL HISTORY OF THE CENTRAL SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: The Sør Rondane Mountains are in some places covered with tills which show various degrees of weathering. According to the degree of weathering, tills are classified into five exposure stages (relative ages), which are roughly correlated with absolute ages obtained by NISHIIZUMI *et al.* (Earth Planet. Sci. Lett., **104**, 440, 1991). On the basis of height and age data of tills, the glacial history in the central Sør Rondane is constructed as follows: (1) A large part of the Mountains was once covered with an ice sheet (prior to 4 Ma); (2) The ice sheet retreated intermittently prior to 1 Ma; (3) In the first half of the last one million years, the ice sheet was stagnant or re-advanced, forming lateral moraines in some places. The ice sheet surface was up to about 100 m higher than the present in that age; (4) Since then, the ice sheet retreated to the level somewhat higher than the present one until tens of thousands years ago.

1. Introduction

Several mountain ranges, 200-400 km inland from the coast of Dronning Maud Land, extend intermittently over 2000 km in an east-west direction and form barriers damming the flow of inland ice. The Sør Rondane Mountains occupy an eastern part of these mountain ranges (Fig. 1). In this Mountains, depositional and erosional glacial landforms are found at various heights. Such occurrence as in the high summit areas of the Mountains implies that the greater part of the Mountains was once covered by an extensive ice sheet. The surface of the ice sheet at its maximum extent was about 400 m higher than the present in the central Sør Rondane Mountains (HIRAKAWA *et al.*, 1988; HIRAKAWA and MORIWAKI, 1990). Periglacial landforms are extensively developed in the Mountains (VAN AUTENBOER, 1964; IWATA, 1987), while geomorphic change by frost action is insignificant at present owing to the very low water content of the ground (MATSUOKA *et al.*, 1990). This suggests that the greater part of the Mountains would have been ice-free and in periglacial conditions for a very long time.

By analyzing cosmic ray bombardment products of bedrock samples collected by JARE-27 (MORIWAKI *et al.*, 1986; Figs. 1, 2), NISHIIZUMI *et al.* (1991) derived several radiometric ages since rocks were exposed from the ice sheet. They concluded that the central Sør Rondane was exposed from the ice for the first time 3 Ma or perhaps earlier.

These exposure ages have provided the first absolute time scale for the elucidation of the glacial history of the inland mountains in Dronning Maud Land.

The degree of weathering of glacial deposits and glaciated rocks is useful for the relative dating of Cenozoic glacial history, because weathering progresses with time. In the McMurdo "Dry Valley" region (Fig. 1), where the radiometric ages of some glacial events had been estimated based on K-Ar ages of volcanic rocks (ARMSTRONG *et al.*, 1968; CALKIN *et al.*, 1970; DENTON *et al.*, 1970), the relative dating and correlation of tills were carried out based on weathering and soil development in tills (LINKLETTER *et al.*, 1973; BOCKHEIM, 1977, 1978). CAMPBELL and CLARIDGE (1987) classified morphological development of soils into 6 weathering stages. In Dronning Maud Land, BARDIN (1969, 1972) classified moraines at 3 different levels in Humboldtfjella (Fig. 1) into 3 stages of glaciation on the basis of relative height above the present ice sheet surface and degree of weathering of tills, and correlated them to the glacial events in the McMurdo "Dry Valley" region. In the eastern Sør Rondane (east of Byrdbreen, Fig. 1), ANIYA (1989) classified the microlandforms of slope produced by weathering and other processes into 3 stages.

We investigated weathering features of tills mainly in the central Sør Rondane Mountains, and classified tills into 5 exposure stages. The purpose of this paper is to estimate the absolute time scale of those stages from the radiometric ages obtained by NISHIIZUMI *et al.* (1991), and then to discuss the glacial history of the central Sør

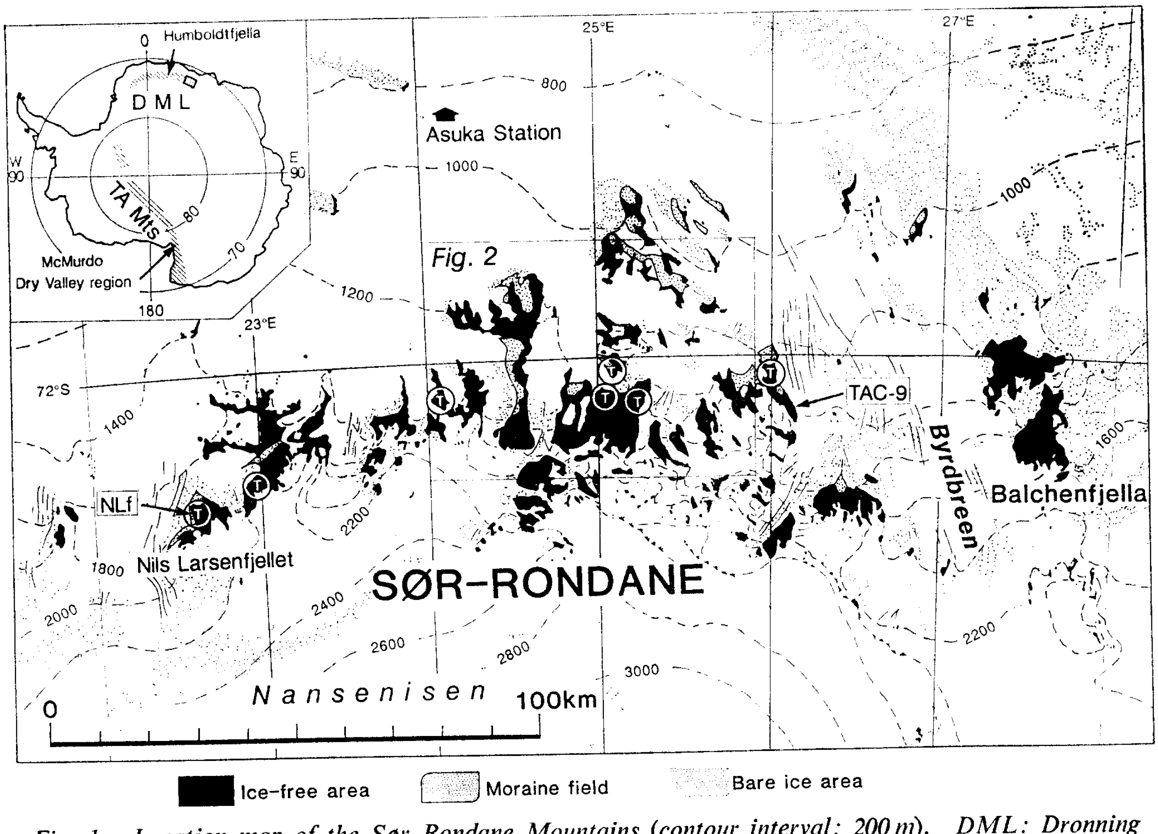

Fig. 1. Location map of the Sør Rondane Mountains (contour interval: 200 m). DML: Dronning Maud Land; TA Mts: Transantarctic Mountains; T in white circle: thick till; NLf and TAC-9: see text.

Rondane. The term "moraine' is restricted to the landforms composed of till in this paper.

2. Tills in the Study Area

The degree of weathering of till was investigated in Lunckeryggen, Brattnipene, Walnumfjellet and Mefjell in the central Sør Rondane, and Nils Larsenfjellet in the western Sør Rondane (Figs. 1, 2). The ice sheet descends from the southern ice plateau (Nansenisen, Fig. 1) attaining to about 3000 m a.s.l. to the northern ice field of about 1100 m a.s.l. along the northern foot of the mountain blocks, forming ice-falls of over 300 m in relative height near the southern margins of mountain blocks. The northern ice field lowers its surface elevation southward at some places along the northern foot of mountain blocks (*e.g.* Brattnipene and Mefjell).

Thin tills cover the mountain slopes in many places, and form moraine fields fringing the mountain blocks at almost same level as the present ice surface. Lateral moraines are found in some restricted places on the mountain flanks. Tills thicker than 40 m were found on the flat summit surfaces of Mefjell, Walnumfjellet and Nils Larsenfjellet (Hirakawa *et al.*, 1988; Moriwaki *et al.*, 1989; Figs. 1, 2).

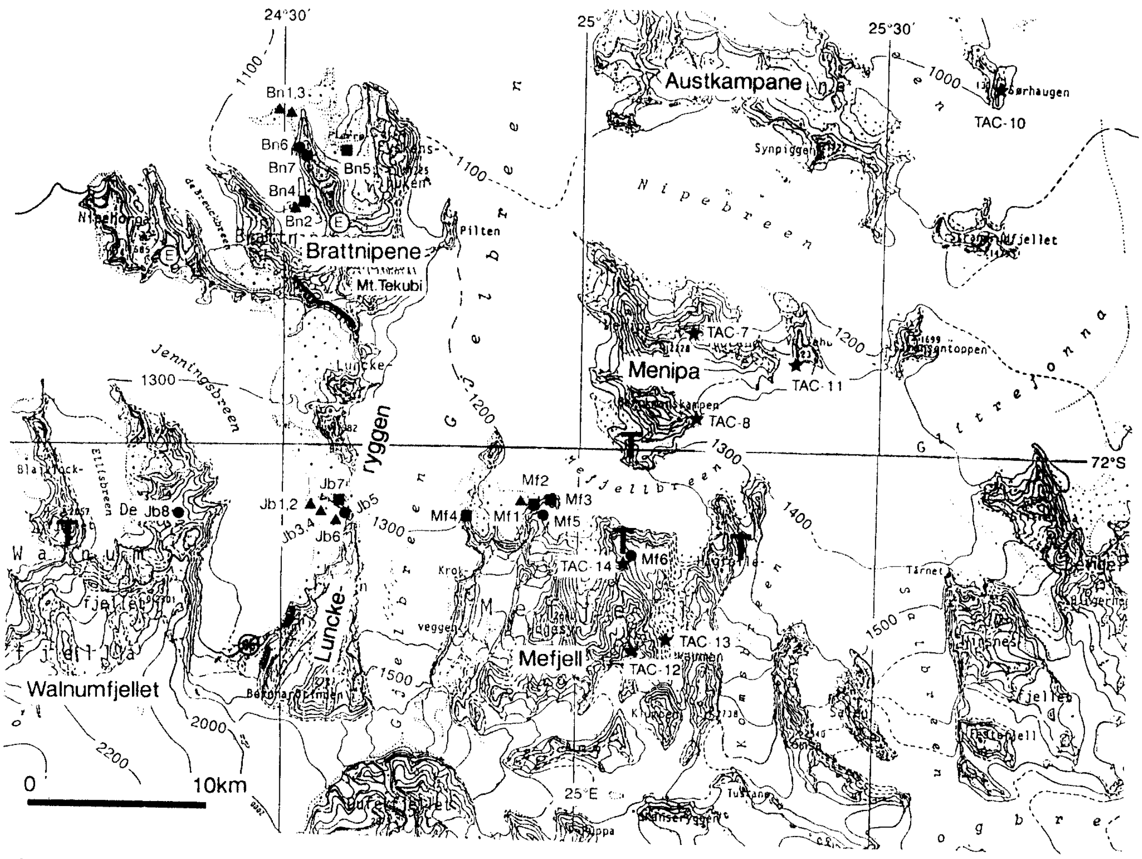

Fig. 2. Main study area in the Sør Rondane Mountains. Triangle: lower till; square: middle till; circle: higher till; star: sampling site for measurement of radiometric exposure age of glaciated bedrock (Nishiizumi et al., 1991); E in circle: erratics of syenite transported from the central Lunckeryggen; asterisk: glacial striae on roches moutonnées.

These tills were classified, according to the relative height from the present ice surface, into three groups as follows: L-till, less than 30 m high; M-till, from 50 m to 100 m high; H-till, more than 150 m high (Fig. 5). In general, the degree of weathering of tills increases with their height above the present ice surface. Weathering of till was investigated at 8 localities from L-tills, at 7 localities from M-tills and at 7 localities from H-tills. The investigated tills in Brattnipene, Jenningsbreen, Mefjell and Nills Larsenfjellet are shown by "Bn", "Jb", "Mf" and "NLf" (Figs. 1, 2), respectively.

Bnl–3, Jb1–4 and Mfl (L-till) which form moraine fields fringing the mountains are supraglacial tills with the flow patterns of the underlying ice. Bn4–5, Jb7 and Mf2–4 (M-till) form lateral moraines on the mountain flanks. These laetral moraines indicate a former level of a stable ice sheet. Jb6 (M-till) forms a terminal moraine shaped by a past local glacier at the foot of the west-facing slope of the central Lunckeryggen. Bn7, Mf5–6 and NLf (H-till) are located on the flat-top summit of the mountains. Jb8 is located in an ice-free valley within Walnumfjellet. Mf6 and NLf seem to be basal tills thicker than several tens of meters. Bn6 and Jb5 form lateral moraines on the west-facing slopes. Around the embayments at the foot of the north-facing slopes of Brattnipene and Mefjell, the present ice surface lowers its elevation toward the insides of the embayments, where the elevations of higher tills are nearly same as those of lower tills located at the outsides of the embayments (Bn5 to Bn1 and 3; Mf5 to Mf4; Fig. 2).

3. Measurement and Classification of the Degree of Weathering

The degree of waetheiing was measured for larger 100 gravels in a quadrangle of 10×10 m on the surface of till. The size and rock type were recorded for larger 30 gravels at the same time. The following items were adopted to indicate the degree of weathering; (1) freshness and staining; A: fresh, B: stained, C: stained and somewhat crumbled, D: strongly stained and crumbled, (2) cavernous weathering such as honeycomb weathering or taffoni; n: no, t: somewhat, T: clear, TT: highly developed, (3) ventifact; n: no, v: somwhat, V: clear. The item (1) is the fundamental criterion of weathering, and the items (2) and (3) are subordinate. According to the combination of these criteria, the degree of weathering (DW) of gravel is classified as follows:

DW 0: fresh
DW 1: stained without cavernous weathering, ventifact and crumbling
DW 2: stained, cavernously weathered and/or ventifacted, not crumbled
DW 3: distinctly stained and somewhat crumbled
DW 4: strongly stained and crumbled.

The characteristics of gravel of DW 0–4 correspond well to those of surface rock of "weathering stages 1–5" by CAMPBELL and CLARIDGE (1987), respectively.

HAYASHI and MIURA (1989) described that shattering and granular disintegration were most predominant among weathering features in the Sør Rondane Mountains. Therefore, it is expected that gravels of schistose rocks become more flat with the progress of weathering. However, we found no relation of size and flatness of gravel to the degree of weathering, perhaps because we measured only gravel of large size. Accordingly, we excluded size and flatness of gravel from the indices of weathering in this paper.

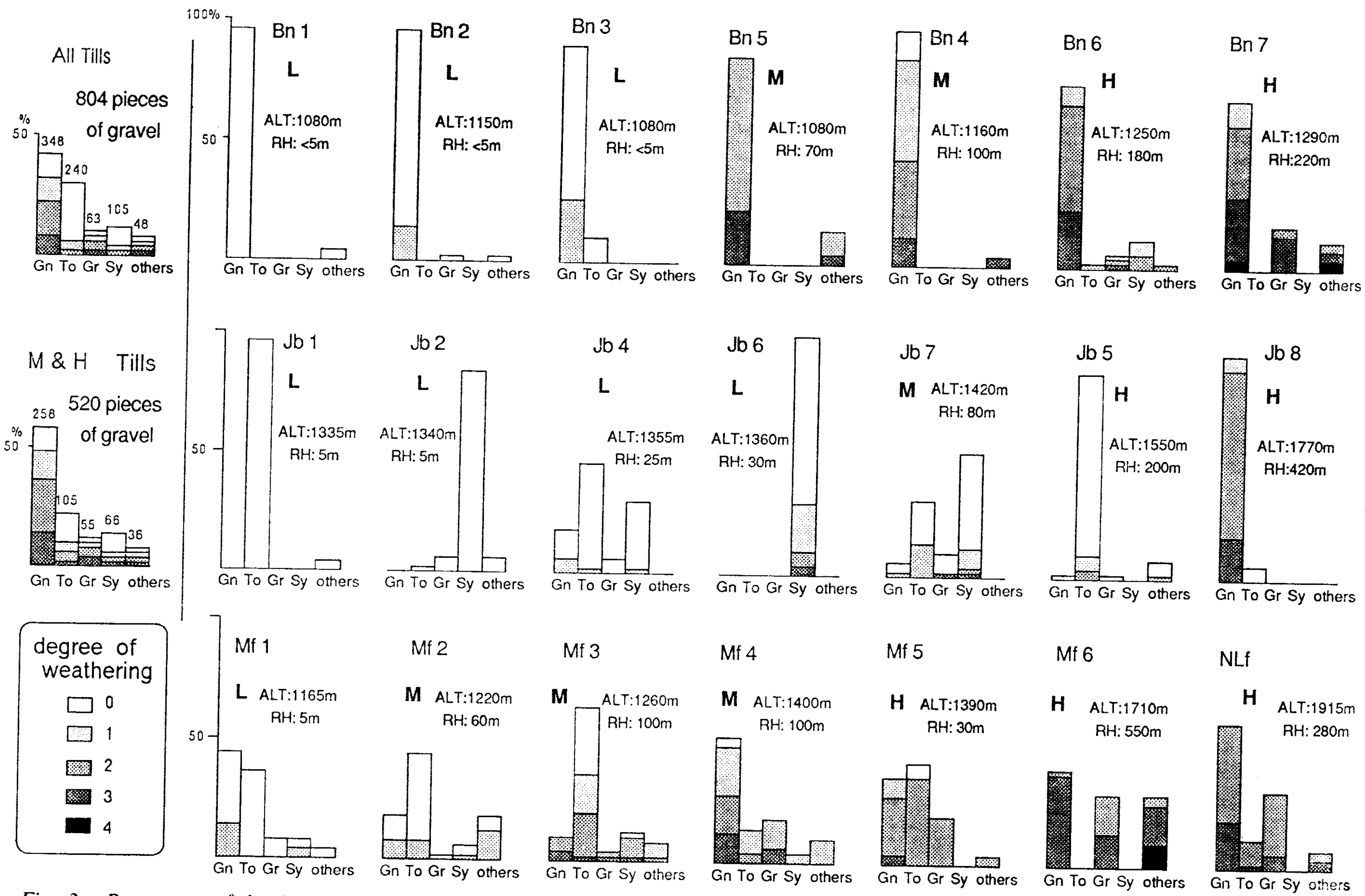

Fig. 3. Percentage of the degree of weathering for each rock type. Degree of weathering: see text. Gn: gneiss, To: tonalite, Gr: granite, Sy: syenite. Bn1–7, Jb1–8, Mf1–6 and NLf are investigated tills shown in Figs. 1 and 2. L: lower till; M: middle till; H: higher till; ALT: altitude a.s.l.; RH: relative height from the surface of present ice sheet.

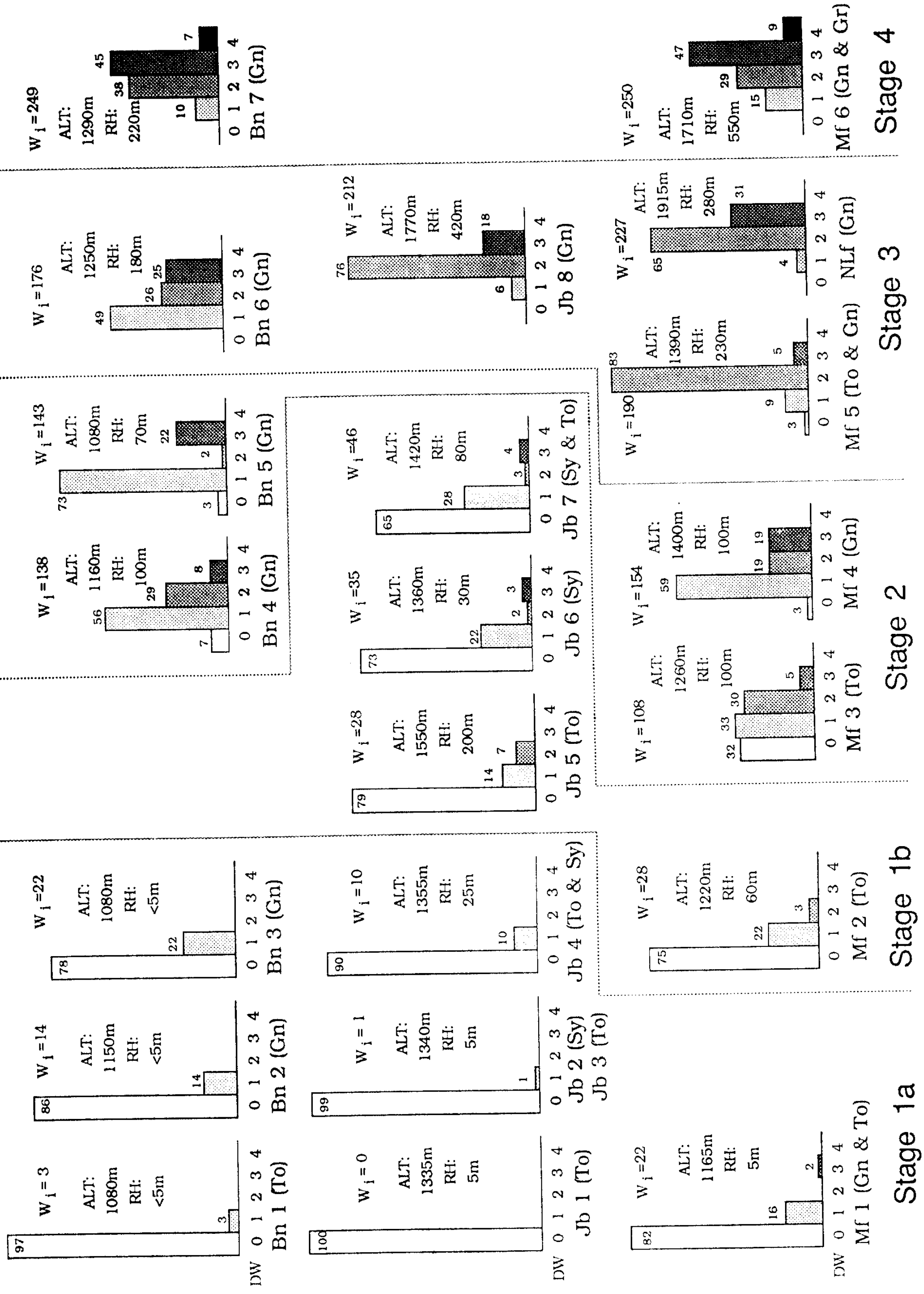

Fig. 4. Classification of weathering stage. W_i: weathering index (see text); DW: degree of weathering of gravel. The figure above a column indicates the number gravels.

Rate of weathering is different among various rocks (*e.g.* CAMPBELL and CLARIDGE, 1987). Figure 3, showing the degree of weathering of gravel classified according to rock types, indicates that gneiss and granite are somewhat easily weathered in comparison with tonalite and syenite. However, we did not consider the influence of rock type in our classification of DW, because of lack of quantitative data on the progress rate of weathering for each rock.

4. Weathering Stage of Tills

The weathering index W_i is introduced here for the purpose of defining the degree of weathering of till. If all the gravels examined show the same degree of weathering, the degree of weathering of till is the same as the degree of weathering of gravels. However, till is composed actually of gravels of different degree of weathering, as shown in Fig. 4. Therefore, we introduce the following value as weathering index;

$$W_i = 0 \times N_0 + 1 \times N_1 + 2 \times N_2 + 3 \times N_3 + 4 \times N_4,$$

where 0, 1, 2, 3 and 4 denote the degree of weathering of gravels (DW), and N_0, N_1, N_2, N_3 and N_4 denote the number of gravels of DW 0–4, respectively.

According to DW and W_i tills can be classified into the following five stages (relative ages):

Stage 1a: almost composed of gravel of DW 0, containing a very few gravel of DW 1. W_i is lower than 25. Bn1–3, Jb1–4 and Mf1 belong to this stage.

Stage 1b: mainly composed of gravel of DW 0 and containing gravel of DW 1, 2 and 3 up to 40%. W_i is between 25 and 50. Jb5–7 and Mf2 belong to this stage.

Stage 2: mainly composed of gravel of DW 1 and containing gravel of DW 0, 2 and 3. W_i is between 100 and 160. Bn4–5, Mf3 and Mf4 belong to this stage.

Stage 3: mainly composed of gravel of the degree of weatheing higher than DW 2, containing few or no gravel of DW 0. W_i is between 170 and 240. Bn6, Jb8, Mf5 and NLf belong to this stage.

Stage 4: mainly composed of gravel of DW 3, containing gravel of DW4. W_i is higher than 250. Bn7 and Mf6 belong to this stage.

Stages 1–4 seem to correspond to weathering stages 1–4 by CAMPBELL and CLARIDGE (1987), respectively. The stage (relative age) of tills advances with their relative heights above the present ice surface except for Jb5, as shown in Fig. 5. The W_i of Mf2, Mf3 and Jb5–7 are small, because they are mainly composed of tonalite and/or syenite which are weathered relatively slowly (Fig. 4).

5. Estimates of Absolute Age Based on Radiometric Ages

We estimated the absolute age of Stage 4 as prior to 2.9 Ma, that of Stage 3 as 2.9–1 Ma, that of Stage 2 as the first half of the last one million years, that of Stage 1b as a rather young period less than 1 Ma, and that of Stage 1a as a period ranging from tens of thousands yerars ago to the present, as follows:

By measurement of cosmic ray bombardment products (^{26}Al and ^{10}Be in quartz), NISHIIZUMI *et al.* (1991) presented several absolute ages when rocks had been freed from

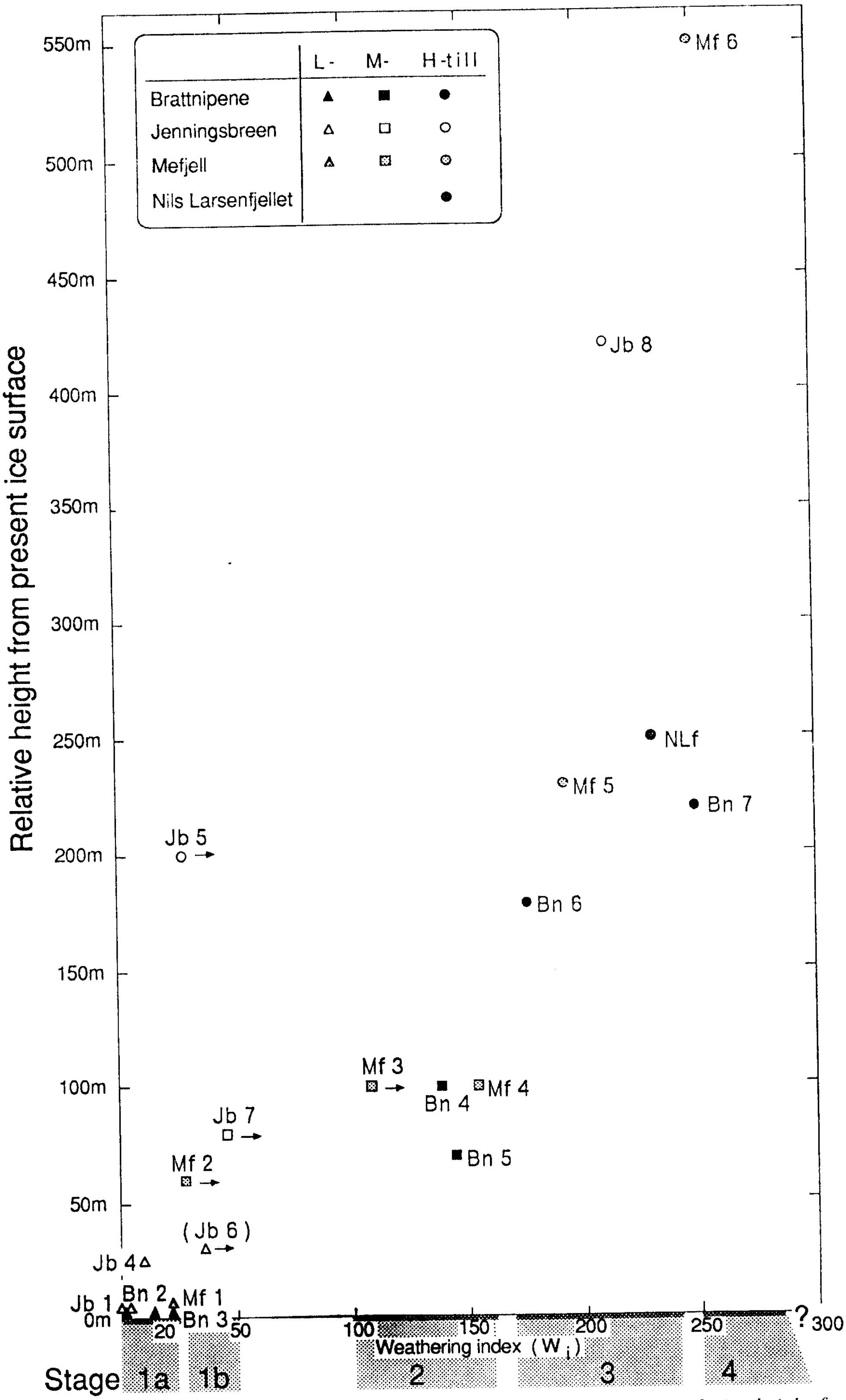

Fig. 5. Relation between weathering stage (relative age) of till and its relative height from the present ice surface. Mf 2, Mf 3 and Jb 5–7 are probably older than the ages presented by W_i, because they are composed mainly of tonalite and syenite which are weathered relatively slowly.

an ice sheet in the central Sør Rondane, and discussed whether glaciation was multiple. Measured eight rock samples were numbered from TAC-7 to TAC-14 by them (Fig. 2). The oldest age of deglaciation was prior to 4 Ma (TAC-14) and the youngest age of that was 36 Ka (TAC-9) in the central Sør Rondane. We plotted these ages on the schematic profile of the central Sør Rondane, and estimated the fluctuation of the ice sheet with time (Fig. 6).

Mf6 (Stage 4) is located at the foot of a ridge where TAC-14 (>4 Ma) was sampled. TAC-13 (2.9±0.9 Ma) was sampled in the U-shaped valley south of Mf6 (Figs. 2, 6). Thus, Mf6 is estimated to have been exposed to the atmosphere sometime during the period from 4 Ma to 2.9 Ma. TAC-11 (0.87±0.09 Ma) and TAC-8 (0.15±0.02 Ma) were sampled from exposed bedrocks about 110 m and 40 m high above the surface of Mefjellbreen, respectively. Mf3 and Mf4 (Stage 2) are located about 100 m high above the present ice surface around Mefjellbreen (Fig. 2). This relative height is nearly equal to that of TAC-11. Therefore, Stage 2 is inferred to be the first half of the period ranging from 0.9 Ma to 0.15 Ma. Tills of Stage 1a are located from 5 m to 0 m above the present ice surface, and TAC-9 (0.036±0.01 Ma) was sampled from an exposed bedrock 3 m high above the present ice surface of Byrdbreen (Figs. 1, 6). Thus, Stage 1a is inferred to be a period ranging from several tens of thousands years ago to the present. Stages 3 is dated between Stages 4 and 2, and Stage 1b between Stages 2 and 1a.

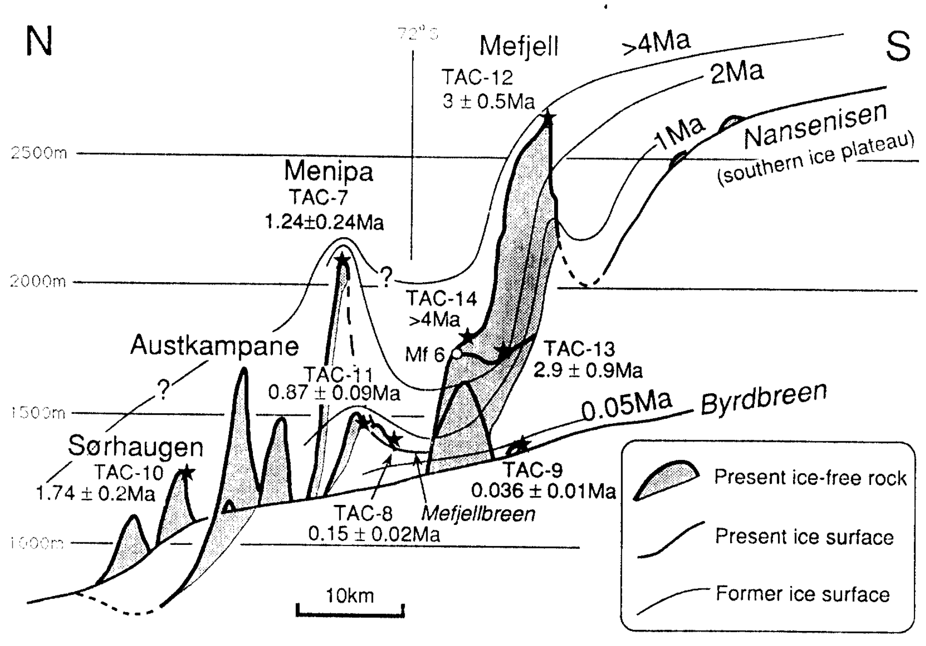

Fig. 6. Former ice sheet profiles inferred from radiometric exposure ages obtained by NISHIIZUMI *et al. (1991), illustrated on a schematic topographic profile of the central Sør Rondane.*

6. Profiles of the Former Ice Sheet

We must consider tectonic and isostatic movements of the Mountains to discuss geomorphic history back to the Pliocene time (SMITH and DREWRY, 1984), but we have no data about them at present. Therefore, the profiles of the former ice sheet shown in Fig. 7 are relative to the present topography.

As Mf6 and Bn7 (Stage 4) are basal tills, the surface of a past ice which transported and deposited them was far higher than their elevation. It is obvious that the period of the maximum glaciation was older than Stage 4, because Stage 4 is the age of exposure of the basal tills from the ice cover. We tentatively assign the period of the maximum glaciation to Stage 5, which was probably older than 4 Ma, judging from the age of TAC-14. The peak of Mefjell, TAC-12 site, was covered by the ice sheet during Stage 5, because its exposure age was measured about 3 Ma (NISHIIZUMI *et al.*, 1991). On the basis of the investigations in the central Sør Rondane, HIRAKAWA *et al.* (1988) and HIRAKAWA and MORIWAKI (1990) concluded as follows: 1) The ice sheet at the maximum stage of glaciation was in general 400 m thicker or more than the present, and the ice fall advanced about 10 km further north at that time than at present. 2) Bernardtinden, the highest peak of Lunckeryggen, was a small nunatak during the period of

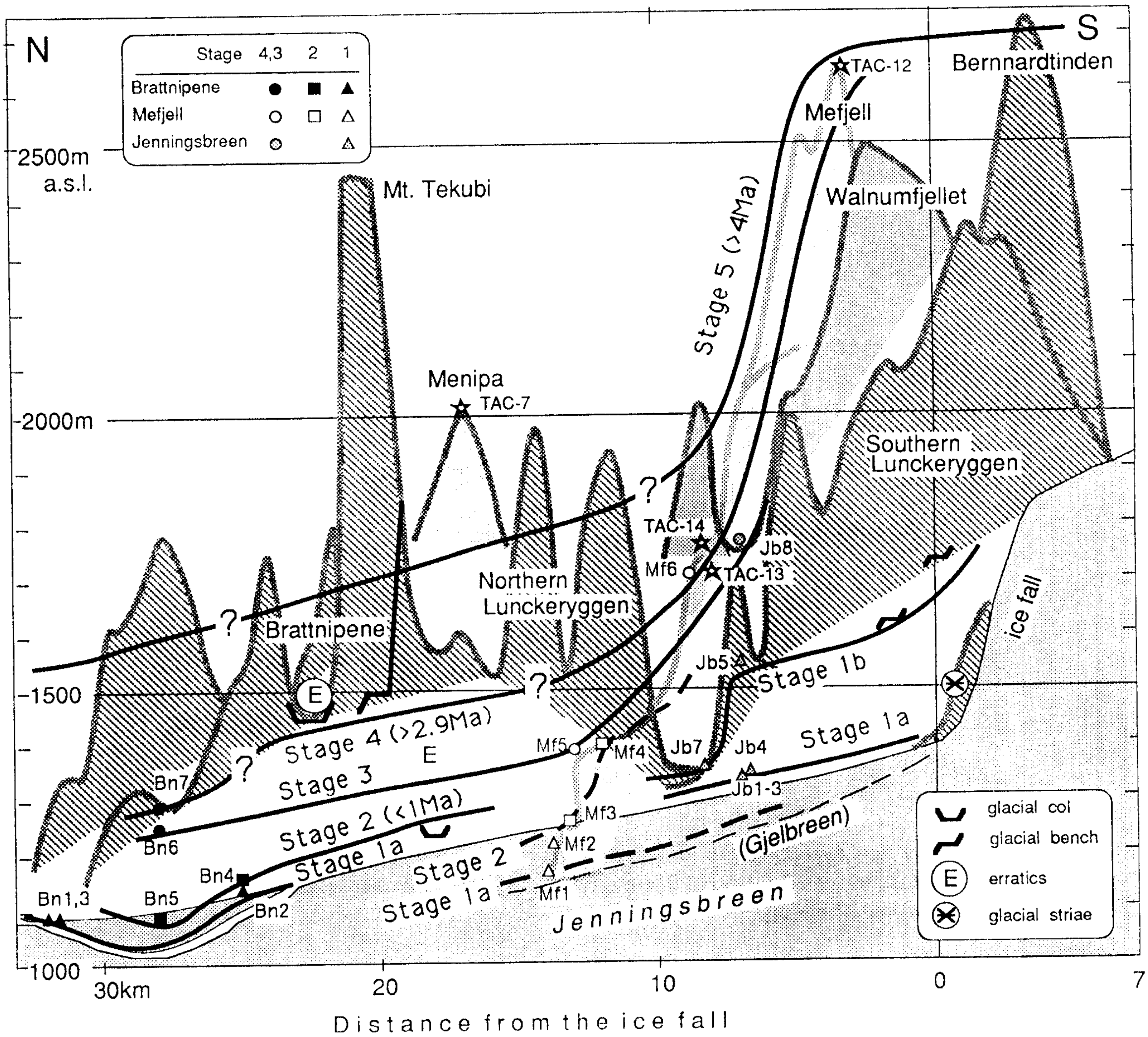

Fig. 7. Schematic profiles showing the change of ice sheet in the central Sør Rondane. Dotted lines: profiles along Gjelbreen.

maximum glaciation. 3) Local glaciers and/or ice caps fed by the drift snow were developed on the higher part of Brattnipene (*e.g.* Mt. Tekubi) and Menipa. The ice profile of Stage 5 was estimated based on these data.

Till weathered to a similar degree to Bn7 (Stage 4) was found on a glacial col to the south of Bn7. This till includes erratics of syenite transported from the south (HIRAKAWA and MORIWAKI, 1990; Figs. 2, 7). The profile of the ice surface at Stage 4 was estimated from the heights of this till, Bn7, and Mf6. The profile of the ice sheet during Stage 3 was estimated from the heights of Bn6, Mf5 and Jb8.

Two kinds of the profiles of the ice sheet during Stage 2 were drawn. One was estimated from the heights of Bn4, Bn5 and a glacial col in the south of them around Brattnipene. The other was estimated from the heights of Mf3 and Mf4 around Mefjell, where the ice fall of Gjelbreen was probably located at the northern margin of Mefjell.

Jb5 and Jb7 forming lateral moraines suggest that the ice fall was located at the northern margin of the southern Lunckeryggen at Stage 1b. Two glacial benches are located to the south of Jb5 along Jenningsbreen with similar relative height above the present ice surface to that of Jb5 (Figs. 2, 7). This suggests that the benches were free from the ice until Stage 1b. Each bench is truncated by a glacial cliff. It is unknown when the benches were glaciated, but the formation of the cliffs postdates formation of the benches. The cliffs were probably formed by a glacier below the level of the benches during and after Stage 1b.

Tills of Stage 1a form thin moraine fields ranging from 0 m to 5 m high above the present ice surface in many places. The profiles of the ice surface during Stage 1a were drawn using their maximum heights in Fig. 7.

7. Ice Sheet Fluctuation in the Central Sør Rondane Mountains

Deglaciation occurred prior to 4 Ma after the glacial maximum (Stage 5) when an expanded ice sheet had covered the greater part of the Mountains. NISHIIZUMI *et al.* (1991) concluded that TAC-7 and TAC-10, -11, -12, -13, -14 were subjected to only one glaciation, but TAC-8 and TAC-9 suffered multiple glaciations. Among the former group, TAC-11 is the youngest (0.87 ± 0.09 Ma) in exposure age from the ice sheet as well as the lowest (110 m) in relative height from the present ice surface. Hence, the ice sheet retreated progressively during the period from 4 Ma to 0.9 Ma (prior to Stage 2), and parts of the Mountains 100 m higher than the present ice surface suffered probably only one glaciation by the ice sheet. It is not clear whether the ice sheet was stable or not at Stage 4, because no lateral moraine at that time was found.

The ice sheet during Stage 3 was stable at least around Brattnipene, because Bn6 forms a distinct lateral moraine. Although the ice fall was located about 10 km north of the present one, the ice sheet was thinner about 300 m than that of the maximum stage (Fig. 7).

Tills of Stage 2, forming lateral moraines in some places, suggest that the ice sheet was stable or re-advanced. The ice surface at that time was nearly at the same level as that of the tills of Stage 2, abuot 100 m above the present ice surface. The profile of the ice sheet is similar to that of the present to the north of the ice fall (Fig. 7). VAN

AUTENBOER (1964) described at least one glacial fluctuation in the Mountains based on the occurrence of glacial gravels in the holes of taffoni on the north-facing cliff of Menipa at about 10 m high above the present ice surface. The fluctuation may have occurred between Stages 3 and 2. As shown by the exposure age of the top of Menipa (TAC-7: 1.24 Ma), the local glaciers on and around Menipa and Mt. Tekubi shrank or disappeared with the decrease of supply of drift snow caused by the general lowering of the ice sheet surface prior to Stage 2.

The ice fall retreated from Stage 1b to Stage 1a, judging from locations of the ice fall at Stage 1b and a moraine field of Stage 1a at the foot of the present ice fall (Fig. 7).

Tills of Stage la indicate that the profile of the ice sheet has been quite similar to the present one since tens of thousands years ago (Fig. 7). Glacial striae rarely remain in the Sør Rondane except Balchenfjella of the eastern Sør Rondane which preserves abundant striae and is regarded to have been exposed recently (Fig. 1; ANIYA, 1989; HAYASHI and MIURA, 1989). N-S trending striae and polished surface remain on roches moutonnées in the lowest part of the southwestern end of Lunckeryggen (Figs. 2, 7). They were probably freed from the ice during Stage 1a, judging from the degree of weathering same as that of gravel of Stage 1a.

8. Conclusion

According to the degree of weathering, tills were classified into five exposure stages. These stages were in good accordance with the absolute ages of the exposure of bedrock from the ice sheet (NISHIIZUMI *et al.*, 1991).

Glacial history in the central Sør Rondane was concluded as follows: During the maximum glaciation prior to 4 Ma (Stage 5), the Mountains with the exception of several high peaks had been covered by an ice sheet. The ice sheet was thicker 400 m or more than the present, and an ice fall dividing the ice sheet into the southern ice plateau and the northern ice field was located about 10 km north of the present one. The ice fall had remained nearly at the same position until Stage 1b. Then, the ice sheet retreated progressively with some pauses (*e.g.* Stage 3) prior to 1 Ma. During Stage 2 (an older period less than 1 Ma), the ice sheet was stagnant or re-advanced, forming lateral moraines in some places about 100 m above the present ice surface. Subsequently the ice sheet retreated to the nearly same level as that at present until tens thousands years ago. The ice fall retreated to the present position from Stage 1b to Stage 1a.

Acknowledgments

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